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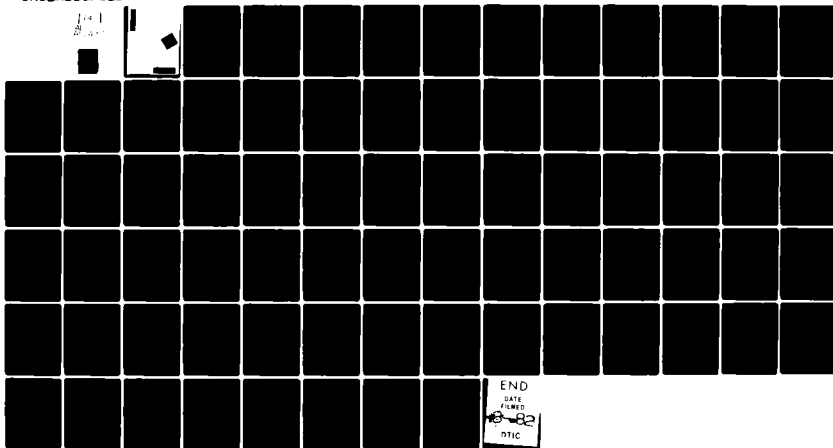
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CONTRIBUTIONS OF REACTION TIME MEASURES TO STUDYING AND UNDERST--ETC(U)  
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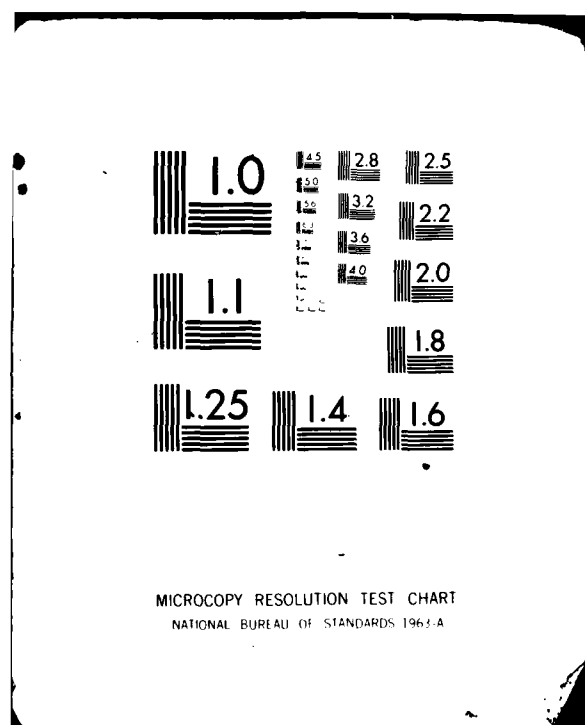
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Contributions of Reaction Time Measures  
to Studying and Understanding  
the Reading Process

QUALIFYING PAPER

SUBMITTED BY

Helen P. Gillotte

May 1981

Harvard Graduate School of Education

## CHAPTER ONE

### INTRODUCTION

The successful, efficient performance of reading, a complex information processing skill, requires that its many components be executed rapidly and accurately in a very short time. If every component process required attention for its execution, then efficient performance would be impossible because the limits of attention and short term memory capacity would be exceeded. It is only when lower level, mechanical aspects of reading can be performed without attention (i.e., automatically) that there are sufficient resources available to allocate to the higher level skills, enabling the entire reading process to be successfully executed and completed.

Assume for the moment that reading can be dissected into components, for example, word analysis processes, discourse analysis processes, and integrative processes (Weaver and Frederiksen, 1980), some of which embody lower level skills and others higher level skills. The relationship between lower and higher level skills is one of sharing limited processing resources. In a series of studies using chronometric measures, (Perfetti and Hogaboam, 1975; Hogaboam and Perfetti, 1978; LaBerge and Samuels, 1974; Frederiksen, 1978h), less-skilled readers have been found to be slower than skilled readers. While this difference may be attributable to limitations in short-term memory capacity (Guthrie, Goldberg, and Finucci, 1972) and attentional-demands of word identification (Doehring, 1976), performance differences within various components also typically take the form of inefficiency or lack of automatic processing on the part of the less skilled reader.

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There are many unanswered questions regarding the development and nature of automaticity of subskills in the area of reading. And, there are related unanswered questions regarding attention, particularly related to selective attention and limited capacity, that are of interest in the area of cognitive psychology. The frequent reference to time or speed of a performance is not due to over-emphasis on the value of rapid work. Time as a dimension of a mental or behavioral process lends itself to measurement and can be an indicator of the complexity of the performance or of the subject's ability to perform. A methodological tool for studying topics of common interest is a necessary, although not sufficient, requirement of both the reading researcher and the cognitive psychologist. Reaction time as a method fulfills this need.

This paper focuses on the contributions of reaction time experiments to studying and understanding the reading process. To accomplish this goal, contributions of cognitive psychologists who use reaction time measures to study topics of common interest to those who study reading is presented. Generally, the study of reading per se is not of primary interest to the cognitive psychologist. However, reading, as a rich, multi-stage, complex mental process, has often been the vehicle through which insights into cognitive processing have been made. Thus, it is extremely valuable to remain abreast of results of experimental psychological research for these results productively inform the work of both reading researchers and cognitive psychologists.

Chapter One presents an historical overview of reaction time measures and addresses the following two questions: what is reaction time? how did reaction time evolve as a dependent variable for measuring speed of mental processes? Chapter Two analyzes memory retrieval and

memory coding processes, topics of mutual interest to reading researchers and cognitive psychologists. For the reading researcher the results of this research led ultimately to the development of more precise models of the reading process. For cognitive psychologists, it led to more detailed information about retrieval of information from memory, the nature of memory representation, and the use of chronometric measures for analyzing mental processes. The principal discussion is limited to an analysis of the major studies in memory scanning research conducted by Saul Sternberg (1966, 1967, 1969a, 1969b, 1975). Second, major findings of Posner and his colleagues (1967a, 1967b, 1969a, 1969b, 1972) that complemented and developed concurrently with Sternberg's work is presented. Chapter Three focuses on the major components of the LaBerge and Samuels (1974) model of the reading process. Its incorporation of features of the research presented in Chapter Two is highlighted. This presentation serves as a backdrop for a discussion of the present state of the art and future applicability of chronometric analysis to understand the reading process, build more precise models of reading, and test hypotheses about the nature of the reading process.



## HISTORICAL OVERVIEW OF REACTION TIME MEASURES

Today when reaction time is mentioned, one generally thinks of a common dependent variable in experimental psychology to measure speed of mental processing. Likewise, one associates reaction time measure almost exclusively with information processing paradigms. Yet, one soon discovers that the history of reaction time antedates the application of experimental methods in psychology, having been undertaken first by astronomers to determine the extent to which individual observers differed in making star transit observations and later by physiologists to determine the speed of nerve conduction.

The period of the astronomer's contributions begins in 1822 with the work of Bessel that established the fact of persistent individual differences in recording the times of star transits (Henmon, 1914). A standard observation in which precision was desirable had been timing the transit of a star across the meridian of a given observatory. The accepted manner of making the observation was the "eye and ear" method.<sup>1</sup> Although instances of unreliability in this method had been reported as early as 1795, it was not until Bessel compared his observations with those of his assistant that attention was given to the variability in star transit observations. Bessel's presentation of the differences between two observers became known as the personal equation. By the use of apparatus for presenting an artificial star and objectively recording the true time of its transit, the error of the single observation was later measured and found to be sometimes positive and sometimes negative.

Some observers tended to get the moment of transit too late, others too early (Woodworth, 1938). Consequently, many astronomers began to confirm Bessel's observation of the unreliability of the "eye and ear" procedure. They attempted to reduce the amount of variation of the personal differences by substituting the chronographic method for the old procedure, thereby making their transit data more precise. The chronograph made the measurement of the personal equation easier. Similarly, the development of the chronoscope provided an additional device for measuring the absolute personal equation.

Along with the development of the new timing devices, another important contribution to reaction measures was made in the 1860's by a Swiss astronomer, Hirsch. Hirsch's engineering colleague, Hipp had just invented the famous Hipp chronoscope, a more precise optical device that measures time in units of milliseconds (msec). With this instrument, Hirsch measured what he called the "physiological time" of sight, hearing, and touch and obtained values which remained fairly standard averages: reaction time to visual stimulus = 200 msec; reaction time to auditory stimulus = 150 msec; and reaction time to electric impulse on the hand = 140 msec (Woodworth, 1938). This was the first comparative research on the subject of time lapse between stimulus and response.

During this period of the 1860's, however, the main interest of astronomers continued to center on the variability of the personal equation. Even though the new chronographic and chronoscopic methods reduced the indeterminate variability of the personal equation, variation persisted. Gradually, it became evident that the nature of the stimulus, its magnitude, rate and direction of motion and the methods

of registration varied the personal equation (Henmon, 1914). More importantly the discovery of so many astronomical conditions of variation suggested that there might be even more, and that the sine qua non had not been even suggested for "it was becoming quite plain that what was needed was not an astronomical, but a psychological, analysis of the variants" (Boring, 1929, p. 142).

Bessel had foreshadowed the need for psychological explanation of the variances in the personal equation. He understood that the time element was important in making observations. His explanation provided the germ of the theory of prior entry, a later psychological doctrine: given two observations, one made later than the other, a difference in timing the events is noticed; the loss of time noted as a result of the differences between the two observations must be accounted for; both observations are similar in their mechanisms; if there is a delay it seems probable that there is actually a delay in both cases; the delay is greater, however, in one than in the other. Bessel suggested that the problem with the delay was in the "locus of the delay." He further hypothesized that the locus was in the mind because of the time consumed by the mind. This explanation becomes important when one considers that most men who thought about the problem at the time considered transmission of nerve impulses to be practically instantaneous (Boring, 1929).

Subsequent investigations of the personal equation by astronomers suggested explanations in terms of the persistence of the visual image upon the retina and the differences in the times of conduction of the auditory and visual impression. The explanation that seemed most adequate, and more in line with the psychological one offered by

Bessel, was based on Hartmann's concept, the central mode of explanation: the observer responds to his expectation of an event and makes the observation even if the event is somehow forestalled.

The significance of Bessel and Hartmann's explanations was that any future analyses of the personal equation problem would inevitably and inescapably be psychological. Expectation, attention, and prior entry theory could no longer be ignored as important psychological factors in explaining individual differences.

In 1830, Nicolai, another astronomer, had sought an explanation for the personal equation in the different velocities of the nervous system, an explanation that had not proved adequate at the time. However, interest in his hypothesis later surfaced and gave impetus to the work of the physiologists. In 1844 Mueller, the leading physiologist of the time, believed that the conduction of nervous action was practically instantaneous and proclaimed that the conduction velocity was unknown. Fortunately DuBois-Reymond, a student of Mueller's sketched in general terms a scheme for such a determination, providing Helmholtz, another Mueller student, with a means of carrying out such measurements.

Helmholtz initially undertook to discover whether electrical methods to measure very short intervals would prove adequate to measure the speed of nerve conduction. He worked on a motor nerve of a frog by stimulating the nerve at two points--one as far as possible from its muscle and one as close as possible to the muscle. In both cases he determined the time that elapsed before the muscle contracted (Donders, 1868/1969). The differences in the times, that is, the time that elapsed between the excitation of two points, indicated the conduction time of the nerve between the two points. From this the conduction

velocity was obtained and found to be 100 feet per second. The time interval between the stimulus and the beginning of the response was the reaction time. It is this research that earned Helmholtz a place in history as the inventor of reaction time.

Numerous investigations on the speed of nerve conduction followed with divergent results. However, the important discovery remained the fact that nervous impulse was not practically instantaneous but relatively slow as Bessel had hypothesized. However, this fact did not intrigue most physiologists at the time, and they, as did the astronomers, lost interest in reaction time measures. Their primary interests continued to lie in eliminating the various differences in the rate of conduction in different parts of the nerves. Many problems remained with the experimental conditions set up by Helmholtz, an important one being that the method supposed that the duration of the process in the brain was quite independent of the place of excitation. Even though the astronomers and physiologists were at this time preoccupied with measuring the personal equation and nervous condition, their investigations nevertheless provided the emerging discipline of experimental psychology with "a problem, some facts, the method, and some apparatus" (Boring, 1929, p. 142).

The psychological interest in reaction time began in 1865 with the experiments of Donders and DeJagger on measuring the times of discrimination and choice. Donders (1868/1969) believed that the function of the mind did not seem to be, nor would it be, included in the "chain of transforming forces" which were the essence of all form of work and energy, that is, motion or the conditions of motion in relation to the law of conservation of energy. He further believed that mental function,

in both form and nature, had a character completely of its own, and that it "does not show a transition or an affinity to other natural phenomena, and the law of conservation of energy . . . is absolutely powerless to bring the mental phenomena under its control" (p. 413). Consequently, Donders believed that mental phenomena could not be measured or evaluated. Sensation, reason, and will could not be expressed in figures. Yet, Donders recognized that even if it would be impossible to obtain complete data as to the nature of the relations of mental phenomena, one should not be deterred from pursuing the possibility that mental processes could be quantified. The factor susceptible to measurement, he suggested, was time, that is, the time required for simple processes.

Encouraged by Helmholtz's research on conduction velocity in the nerves, and the fact that this work offered solution to problems which had been considered insoluble, Donders pondered an intriguing question of long standing: Would thought also not have the infinite speed associated with it, and would it not be possible to determine the time required for shaping a concept or expressing one's will? (Donders, 1868/1969, p. 417).

In Hirsch's initial studies on the propagation of velocity in sensory nerves, the time that lapsed between the stimulus and the response included a particular mental process. The time was called physiological time and found to be shortest after stimulating the skin, longer after stimulating the ear, and still longer after stimulating the eyes. (See Table 1). Donders confirmed Hirsch's findings.

Table 1  
Measurement of Physiological Times

	Donders	Hirsch
Touch	142.8 msec	140 msec
Hearing	166.0 msec	150 msec
Vision	200.0 msec	200 msec

Donders also discovered that the whole process of physiological time could be completed in 142.8 msec and even 111.0 msec as a minimum. The unanswered question, however, was what proportion of this time formed part of the mental process proper? For example, if the skin, ear, or eye were stimulated, and the process from the moment of the stimulus to moment of response were followed, twelve stages would be distinguished (See Appendix I). However, the times for each of the separate stages could not be determined. In thinking about this problem, Donders wondered what would occur if he interposed into the process of physiological time some new components of mental action. "If I investigated how much this would lengthen the physiological time, this would, I judged, reveal the time required for the interposed term" (Donders, 1868/1969, p. 418).

Three identical experiments were carried out. In Experiment I identical electrodes were placed on both feet of the subject. By using a Pohl seesaw, an electrical impulse could be delivered to either foot. Two conditions were executed: in the first it was known to which foot the stimulus impulse was to be offered, and a response was to be made by the hand on the same side; in the second it was not known to which foot the impulse was to be offered, but the response had to be made by

the hand on the stimulated side. In the latter case, more time was required than in the first, and the difference represented the time required for deciding which side had been stimulated and for establishing the action of the will on the right or left side. This experiment was the first determination of the duration of a well-defined neural process. It concerned the decision in a choice and an action of the will in response to that action (Donders, 1868/1969).

Experiments II and III were carried out with stimuli acting on the senses of vision and hearing, respectively. In Experiment II the physiological time was ascertained with a simple response to light and with a differential response to a red and white light. An expanded version of Experiment II was carried out in which the stimuli were special letter-symbols, either uncovered or suddenly illuminated by an induction spark, and the response was pronunciation of the sound. In Experiment III, the ear was stimulated with the sound of a vowel and the response was the repetition of the same vowel. In every case, the decision in the choice and the related response appeared to require more time than in the previous simple response experiments.

Table 2  
Donders's Figures for Simple Response Compared To  
Differential Responses for the Three Senses

	Simple RT (a-reaction)	Choice RT (b-reaction)
Vision	200 msec	.154 sec = 154 msec
Hearing	166 msec	.056 sec = 56 msec
Touch	142 msec	.066 sec = 66 msec



Another component of Donders' first series of three experiments was that the conditions for each sense were also carried out with two or more stimuli, for example, the subject had to discriminate between five vowel-symbols with the eye or five vowel-sounds with the ear (See Appendix II). After Donders measured the combined time lapse in two or more stimuli, in which even more time is required, he began to consider whether he could separate the two stages and establish the time for each stage. The obvious solution appeared to be to make a condition in which a response should be made only to one stimulus, ignoring the others. Donders chose vowel-sounds as the stimuli, but only one--the i--was to be responded to. Donders served as his own subject in this experiment. The conditions of this experiment were: (a) responding to a known sound; (b) responding to an unknown sound; and (c) responding to one of the unknown sounds (See Table 3). He listened carefully for the recognition of i and kept the "position of the parts of the mouth and the mechanism ready so that, upon recognizing the i, he had only to breathe out to produce the corresponding sound, just as in the case where a subject knowing that i was to be heard had to respond with i" (Donders, 1868/1969, p. 423). According to Donders this experiment required no choice for the response; only the distinction, the recognition of i, was interposed in the normal process. The overall result of this experiment showed that less time was required for responding to each vowel sound with the identical sound. A similar experiment was conducted using the 'c' reaction, when the stimulus was 'seeing' a vowel-symbol. Donders found the time required for recognition to be rather short, "scarcely longer than with vowel-sounds" (p. 425).

Donders anticipated that he might be questioned as to the differences in choice times due to the particular sense stimulated. He suggested that the response given to sound is a simple imitation which had become natural by training, more so than the conventional response with the right or left hand in the case of differences in color. He also carried out a number of experiments which proved that the physiological times for sound and light did not noticeably diverge. His suggestion was that prolonged training resulted in higher speed of response in the color experiments.

In summary, Donders was the first to attempt a determination of the speed of judgement, choice, and discrimination. This reaction experiment involved the measurement (by an electrical clock or by graphic registration, which Donders used) of the duration of the whole chain of processes from the moment of stimulation to the execution of the movement. A reaction is a movement made in response to a sense impression. If it follows immediately after the reception of the impression, the reaction is said to be simple; if some further conscious process is interpolated between sensation and motor innervation, the reaction is said to be compound. The results of his various experiments led him to distinguish between three significant reaction times. Reaction time 'a' involved a single stimulus and a single response that was required whenever the stimulus occurred. This is referred to as simple reaction time (RT). Reaction time 'b' involved two stimuli and two responses. This task was the prototype of the choice reaction time paradigm (CRT). Reaction time 'c' (a version of CRT) involved two stimuli and one response. Donders took the results of the three series of experiments as evidence that reaction time measures could be used to determine the time

required for conceptual processing. He based his hypothesis on two assumptions: that distinct subprocesses or stages operated (later known as stage theory) and that no overlap occurred among processes (pure insertion tasks). For example, reaction time 'b' involved three processes according to Donders: (1) simple reaction time 'a', the time to respond to a stimulus; (2) stimulus categorization, the time to decide which stimulus was presented (choice); and, (3) response selection, the time needed to select the right key. The 'c' reaction, on the other hand, included only stimulus categorization, thus the differences between 'b' and 'c' was that the 'c' reaction did not include response selection.

Reaction times can exhibit a substantial amount of variability from trial to trial. However, by averaging over many trials and by carefully controlling the experiment so as to exclude any extraneous factors, it is possible to obtain stable estimates of the times of the various tasks. Donders attempted to ensure reliability by conducting 51 series of these experiments, often using himself as an experienced subject. Thus Donders was able to average the reaction times from his experiments to obtain the results shown in Table 3. Donders then subtracted the 'c' reaction from the 'a' reaction to determine the time occupied by sensory discrimination (stimulus categorization) and the 'b' reaction from the 'c' reaction to determine the time needed to select the right key (choice). This method of measuring the time needed for conceptual processing became known as Donders' Subtraction Method and was the first such method for determining that stages of mental processing occur and for recording the durations of each.

Table 3

## Donders' Subtraction Method

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 reaction time 'a' = 201 msec

reaction time 'b' = 284 msec

reaction time 'c' = 237 msec

c - a = 36 msec, the time occupied by sensory discrimination

 b - a = 47 msec, the time occupied by response selection
 

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In other words, the RT is the sum of the duration of the stages. To use the subtraction method, one devises two tasks; the simple reaction task that involves one stimulus and one response, and the choice reaction task, which requires the operations of the simple reaction

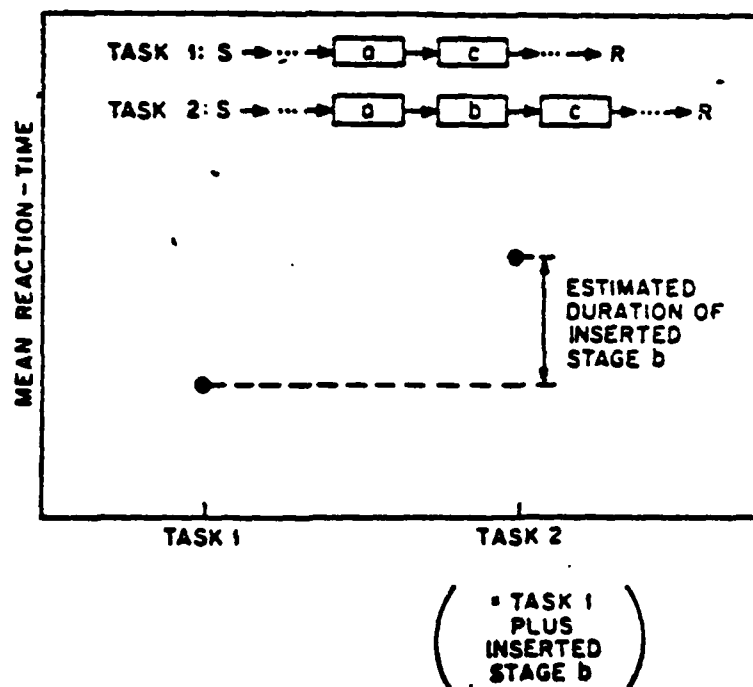


Figure 1. Donders' Subtraction Method. Hypothetical stages between stimulus (S) and response (R) are represented by a, b, and c (Sternberg, 1969b).

plus an additional inserted operation. The difference between RTs in the two tasks is interpreted as an estimate of the duration of the inserted stage. However, this interpretation depends on the validity of the stage theory and the assumption of pure insertion which states that changing one task to another merely inserts a new processing stage without altering the other two.

It is this work by Donders that evolved into one of the most durable assumptions in experimental psychology: that the time between stimulus and response is occupied by a train of processes or stages--some being mental operations--which are so arranged that one process does not begin until the preceding one has ended.

#### VALIDATING THE ASSUMPTIONS

The continuing history of the development of reaction time measures is concerned to quite an extent with validating Donders's two main assumptions, stage theory and pure insertion. Wundt, the founder of the Leipzig Laboratory, had conceived the idea of an experimental psychology. He thought that the work already accomplished by the physiologists on the senses, muscular movements, and nervous systems could be the starting point for his new psychology, and that the methods used by physiologists could be used to study mental processes. Introspection would remain essential in psychology, but it would be supplemented by experiment in order to unravel the complex phenomena revealed by introspection. Wundt began by thinking he could use the results of Hirsch's physiological research and the results of physiologists working on the personal equation. Later in 1874, however, he discarded that work as insufficient and turned to the results obtained by Donders. Wundt

thought, however, that Donders had erred in his assumption that no motor or choice element was involved in the 'c' reaction. He attempted to expand Donders' three reaction tasks by inventing a fourth, the 'd' reaction, which he called cognitive reaction. The 'd' reaction would differ from Donders' 'a' reaction (simple) by the insertion of discrimination only. Wundt planned to use the simple reaction as a base line and to complicate the process a step at a time, thereby capturing the time required by various mental processes.

Wundt conceived of the simple reaction as including a sequence of three processes: (1) entrance of the sensory impression into the field of consciousness; (2) entrance into the focus of attention; and (3) the voluntary release of the signaling movement, the response (Boring, 1929). However, Wundt, could not conceive of any possible way of timing these three processes separately. Yet, he thought the next step after the simple reaction was the 'd' reaction. The difference between the 'd' reaction and the 'a' reaction would equal or represent the time occupied by discrimination or cognition. The Donders' 'b' reaction included discrimination and choice, and 'b' minus 'd' would give choice time. Association time could be found by requiring the subject to signal at the moment when an idea reproduced by association made its appearance in consciousness. Subtracting the 'd' reaction from the associative reaction would give the time occupied by the process of association.

Initially the studies testing the 'd' reaction were encouraging. However, later experiments produced suspiciously short or even zero recognition time for association or they resulted in no differentiation between the 'd' reaction and the simple reaction, 'a'. In 1886 Berger

tapped the source of trouble by proving that the motor response in the 'd' reaction was not dependent on the identification of the stimulus for the response was the same for all stimuli. Wundt's conception was that in the simple reaction the subject signaled as soon as he became aware of a stimulus, while in the 'd' reaction the subject signaled when he recognized or identified the stimulus. However, Berger pointed out that in the 'b' reaction each stimulus called for a different motor response; in the 'c' reaction one stimulus called for a movement and the others for no movement; and, in both these forms the reaction would often be false unless held back until the stimulus was identified. No such check was available for the 'd' reaction. Certainty about the discrimination having actually taken place at the time the reaction movement is released is possible only if the movement depends on the discrimination. There is nothing to prevent two mental processes from occurring simultaneously. Two responses, one perceptual and one motor, may take their start simultaneously from the same stimulus. Berger argued that if the motor response were not made to depend on the perception, it could start at once, as in the simple reaction, a finding that had already been discovered (Woodworth, 1938).

Many attempts were made during the late nineteenth century to further explore the validity of Donders' assumptions. However, Wundt's inability to devise pure insertion tasks, coupled with the continued use of introspection to study mental processing sounded the death knell for the subtraction method, for subjective reports could not be relied upon as providing the order of occurrence of psychological processes.

It is not within the limits of this chapter to detail the extensive research that eventually validated the use of the subtractive

method and reaction time measures. The attempt has been restricted to discussing those events which led to its ultimate emergence in the twentieth century as a paradigm for studying cognitive processes. Chase (1974) suggests, in retrospect, that the lack of success with the subtractive method was ultimately due to the absence of a good cognitive theory. The lack of a sound theory made it inevitable that processes such as cognition, association, and attention would fail to emerge as analyzable mental operations with measurable durations.



## CHAPTER TWO

### MODERN INTEREST IN REACTION TIME MEASURES

Interest in reaction times increased once again during the Second World War. Two forces, engineering psychology and information theory, revived it. Engineering psychologists became interested in the performance of well-learned skills and in promoting maximum performance from workers. They thought the reaction time task was a pure measure of error-free performance, one that truly measured the limits of a performance. Information theorists were interested in factors that limited speed. In their case, the interest was in measuring the speed of information transmission over a limited-capacity channel. Together, information theorists and engineering psychologists shared a contemporary information-processing interest in human performance. As human performance researchers, they were the first to see the value of the computer analogy, revive Donders' Subtraction Method, and begin to design experiments to find out about internal processes (Lachman, Lachman, & Butterfield, 1979).

The use of reaction time measures is today almost exclusively associated with an information processing paradigm. This paradigm for studying cognition holds that the path from sensory input to motor or conceptual response proceeds through a series of discrete processing stages, each of which can, in theory, be identified. A contemporary use of reaction time to study cognitive processing is the modern choice reaction time research that grew out of efforts by psychologists to resolve a theoretical dispute intrinsic to cognitive psychology: whether stages of mental processing are executed serially

or in parallel. A major contributor towards a plausible resolution of this dispute has been Saul Sternberg.

Human memory traditionally has been studied by examining how and when it fails by considering the frequency and pattern of errors in recall or recognition. Because these errors may occur from failures of learning, retention, or retrieval, a very real difficulty of the traditional approach to studying memory is disentangling the alternative sources of error (Sternberg, 1975).

A complementary approach to the study of memory is the examination of memory under conditions in which it functions successfully and produces performance that is virtually error-free. Sternberg (1966) began his research in human memory by investigating memory retrieval processes. He began with the supposition that if information in memory is used to make a response, response latency would tell something about retrieval processes. Of particular interest in memory retrieval is the effect the size the memory set has on response latency. Thus, identity of the items is important rather than their order. The paradigm devised by Sternberg is a memory-scanning task (later adapted and used as an item recognition and a character classification task) in which the subject is asked to memorize a series of elements, generally ranging in number from 1 to 6, called the memory set. The subject is then shown a test stimulus (or probe) and is asked to state whether it is in the memory set. If the subject decides in the affirmative, he pulls one lever making a positive response; if he decides otherwise, another lever is pulled making a negative response. The response latency is defined as the time from the onset of the test stimulus to the occurrence of a response. Using this paradigm (See

Figure 2), Sternberg conducted a series of experiments that stimulated the interest of cognitive psychologists to study mental processing using choice reaction time tasks as the dependent variable.

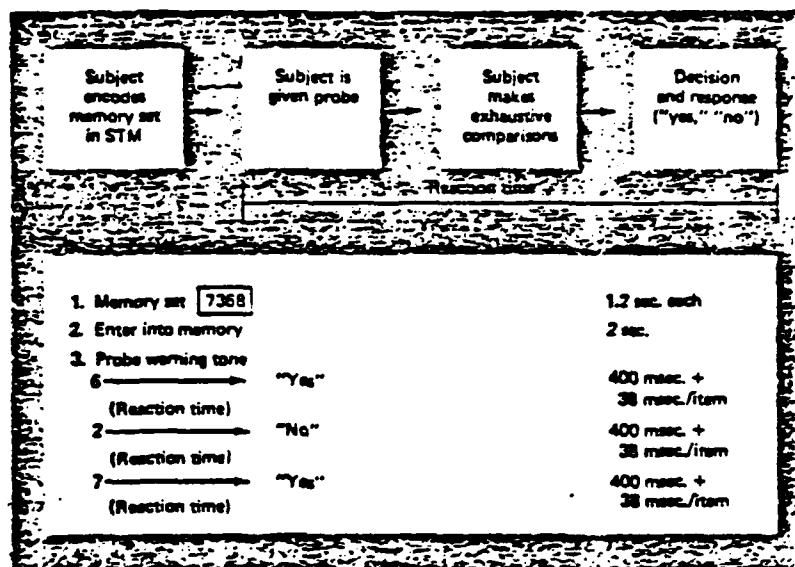


Figure 2. Sternberg's memory scanning paradigm. (Solso, 1979).

The first reported set of experiments (1966) was undertaken to study how symbolic information was retrieved from memory. In experiment 1, each subject participated in 24 practice trials and 144 test trials. On each trial the subject saw a random series of from one to six different digits displayed one at a time at a fixed locus and presented for 1.2 seconds each. The ten digits were used because of their familiarity and because these experiments measured error-free, highly learned performance. The length of each series varied at random from trial to trial. After each presentation there followed a 2.0 second delay, a warning signal, and then a test digit. As soon as a response was made a feedback light informed the subject if the

response were correct. Each trial ended with an attempt to recall the series in order. (Because the results of experiment 1 are practically identical with those in experiment 2, the second experiment will be described before discussing results.)

In experiment 1 Sternberg used a varied-set procedure, that is, the set of symbols associated with the positive response (in the memory set) changed from trial to trial. In contrast, in experiment 2 a fixed-set procedure was used whereby the set of symbols associated with the positive set remained the same. This experiment also more closely approximated the choice reaction time task. The subject knew that on each trial any of the ten digits could appear as the test stimulus and that for all digits not in the positive set, the negative response was required. In each of the three parts of the session, a set of digits for which the positive response was required was announced to the subject. There were 60 practice trials and 120 test trials. Memory set digits were 1, 2, and 4 in size.

Results of the two experiments are shown in Figures 3 and 4. In experiment 1, the slope of the fitted line is  $37.9 \pm 3.8$  msec per symbol; its zero intercept is  $397.2 \pm 19.3$ . In experiment 2, the slope of  $38.3 \pm 6.1$  msec per symbol is indistinguishable from that in experiment 1; the zero intercept is  $369.4 \pm 10.1$  msec (Sternberg, 1966). In both experiments, reaction time increased linearly with the number of digits in the memory set. Linearity, as the slope of the line, represents the time taken to scan each item. In other words, the time per item scanned does not change from one end of the list to the other. The slope is therefore a relatively pure measure of the time required to process information.

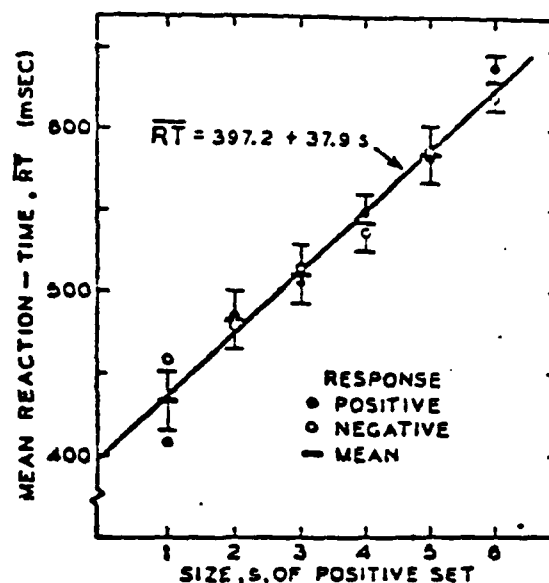


Figure 3. Results of Experiment 1 with varied-set procedure. Mean latencies of correct positive and negative responses, their mean, as functions of size of positive set. About 95 observations per point (Sternberg, 1966; 1969).

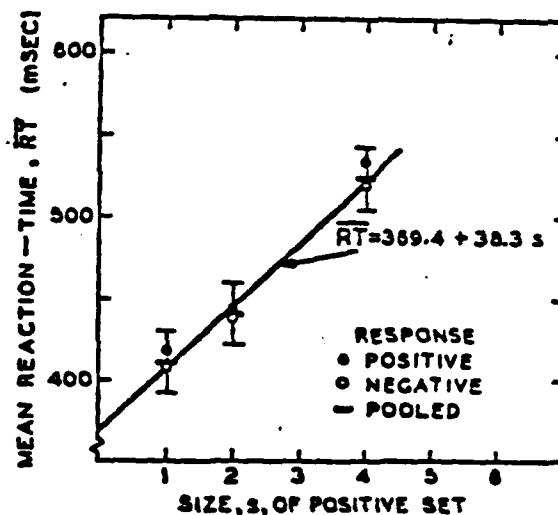


Figure 4. Results of Experiment 2 with fixed-set procedure. Mean latencies of correct positive, negative, and pooled responses as functions of size of positive set. About 200 (positive) or 500 (negative) observations per point (Sternberg, 1966; 1969).

Although it did not seem surprising that a larger memory set resulted in a longer reaction time, another finding was surprising and significant. It was discovered that the reaction times changed uniformly according to the number of items in a set. Each new item in the memory set seemed to require a fixed amount of processing time and that amount was cumulative with other processing times. In the case of experiments 1 and 2, the time required to process each additional item in the memory set was 38 msec. The slope was not affected by the time required to begin scanning, to decide upon a response, or to make a response. These factors affected only the intercept of the fitted line--its height above the x-axis. It stood to reason then that the positive set (fixed-set) in experiment 2 played the same role as the series of symbols (varied-set) presented in experiment 1. This suggested also that practice with the memory set affected neither the zero intercept nor the slope of the linear functions.

Based on the results of experiments 1 and 2, Sternberg posited that linearity of the latency functions demonstrated that time between test stimulus and response was occupied, in part, by a serial comparison (scanning) process. That is, the results furnished evidence that an internal representation of the test stimulus was compared successively to the symbols in memory, each comparison resulting in either a match or a mismatch. The time from the beginning of one comparison to the beginning of the next had the same mean value for successive comparisons. A positive response was made if there was a match, and a negative response if there was not.

In addition to proposing that memory search proceeded serially, Sternberg further proposed that it was exhaustive rather than self-

terminating. Exhaustive search means that the subject looks at every item in the memory list before deciding whether the target is on the list. Self-terminating search means that the subject stops the comparison as soon as a match is made. Based on the results in Figures 3 and 4, it can be seen that the slopes for positive and negative responses are relatively equal. This equality of positive and negative responses provided the evidence for exhaustive search.

Sternberg assumed that in the memory search process a test item was presented, the subject identified it, then compared it with each item in memory in a serial fashion, one item at a time, and then selected a response. He then identified the zero intercept as the sum of the times needed for identification of the test stimulus, for a response, and other unknown processes whose durations were independent of the number of symbols in memory. The slope represented the mean comparison time. In developing a theory of exhaustive search, Sternberg hypothesized that the identification stage and the final response stage took a fixed time,  $b$  msec. The predicted time for a negative trial would be the same for a self-terminating and an exhaustive model. For example, if each memory comparison took  $a$  msec, the negative reaction time would be equal to the base time ( $b$  msec) plus the comparison time multiplied by the memory set size ( $s$ ).

$$RT- = b + a(s)$$

If the test item were not in the list, the subject had to compare it with all  $s$  items in the list before reaching a decision. This prediction meant that reaction time should increase in a linear fashion with  $s$ . For a positive trial the prediction time in an exhaustive search would be

$$RT+ = b + a(s)$$

just as is the negative reaction time. Each test item would be compared with each item in the memory set. Even if a new data set were allowed only the zero intercept would be affected. The important feature of the exhaustive search model is that  $RT+$  and  $RT-$  are linear functions with the same slope parameter  $a$ . (See Figure 5.) On the other hand, assuming that the memory search is self-terminating,  $RT+$  would increase about half as fast as  $RT-$ .

$$RT+ = b + a\left(\frac{s+1}{2}\right)$$

That is, if  $s$  were 1,  $RT+$  would equal  $b$  minus  $a$ . The one item in memory would match the test item, and so a single comparison would produce a match. If  $s$  equaled 2, there would be two items in memory, one of which matched the test item. Half of the time, the first item chosen from memory for comparison would be the matching one. The other half

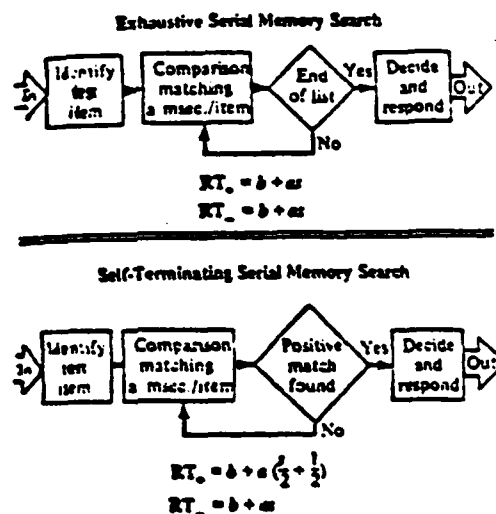


Figure 5. An information processing model for two kinds of memory search, in which  $b$  is base time required by identification and response stages,  $a$  is memory comparison time per item, and  $s$  is number of items in memory list (Calfée, 1975).



of the time the first item selected would not be the matching one, and so two comparisons would have to be made with the test item.

In summary, mean latencies of both positive and negative responses increase linearly with the number of characters in the memory set; the mean increase in latency per character is approximately the same for positive responses as for negative responses (e.g., 38 msec per item and 25 to 30 characters scanned per second) and this equality supports serial, exhaustive search process rather than self-terminating.

Having satisfied himself as to how symbolic information was retrieved from memory, Sternberg turned next to a consideration of how that information is represented in memory. He began with the following situation: at some point between test stimulus presentation and response, a representation of the stimulus encounters a memory representation of the monitored character and the two are compared. If this is so, the problem, as Sternberg saw it, was: what is the nature of the encoded stimulus? And, in the formation of this representation, how much analysis of the stimulus is carried out? (Sternberg, 1967).

Sternberg began with an idealized form of the results of his previous experiments (See Figure 6). Recall that he had identified the slope with the comparison time of the stimulus representation to the memory representation and that the zero intercept with stimulus perception and identification, decision, and response selection. Assuming the validity of the scanning theory, Sternberg interpreted these parameters as representing different cognitive processes. These processes were called Operation 2 and 1, respectively, Operation 1 being carried out only once, and Operation 2 several times, once for each item in the positive set. Sternberg maintained that these processes were

independent and that tasks could be devised to affect both the zero intercept and slope without interaction occurring.

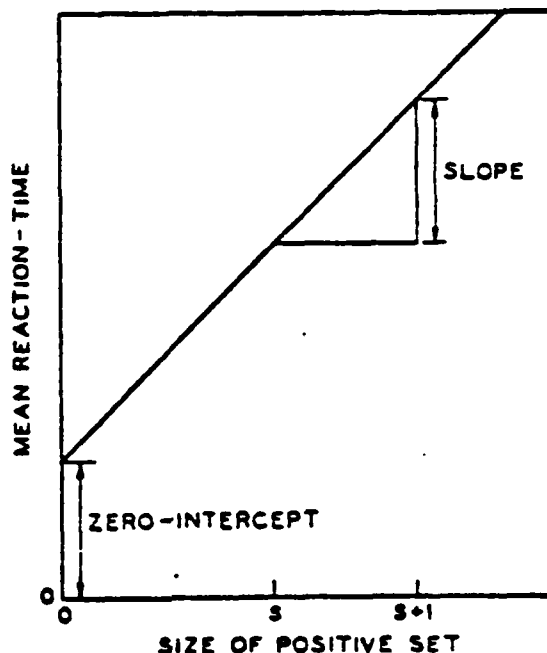


Figure 6. Idealization of mean RT function (Sternberg, 1969).

In undertaking this task, Sternberg surveyed alternative theories of the character recognition process. He looked at three broad classes, each of which depended on a particular kind of stimulus representation: (A) theories of raw images, (B) theories of refined images or feature list, and (C) theories of imageless concepts or images of a spoken name. Sternberg reasoned that for a test of Class A theories, the zero intercept would be unaffected because it would transmit an unprocessed image or an exact replica of the test stimulus. Any increase in reaction time would be due to the comparison process and not the encoding process. He reasoned second, and at the other extreme, that a test of Class C theories, for which the test stimulus was a sufficiently processed

version of the stimulus represented in memory, for example, a name, any increase in reaction time would have to be accounted for in the encoding process. Therefore, a stimulus of the Class A type could only be affected by the encoding stage. On the other hand, a test of the Class B type could affect either the encoding or the comparison stage.

Sternberg used his scanning paradigm, specifically termed character-recognition for this set of experiments, with one change. Sometimes the stimulus was presented in degraded form, the test stimulus being manipulated by the superimposition of a checkerboard pattern; other times the stimulus was presented intact. Sternberg proposed to determine the difference between reaction times to intact and degraded test stimuli for positive sets of size 1, 2, and 4. Each trial consisted of an inter-trial interval of 2.0 sec, a warning signal for 1.25 sec, and display of the test stimulus for 44 msec, either degraded or intact, the subject's response, and a feedback light displayed for 0.75 sec from occurrence of the response.

The results are shown in Figure 7. As predicted, degradation of the test digit has a much larger effect on the intercept (encoding) than on the slope (comparison) of the linear function. On Day 1, there is a slight effect of degradation on the slope parameter; however the striking feature is the shift of the intercept, about 65 msec. On Day 2 the slope parameter is virtually identical for intact and degraded test digits, showing again approximately 60 msec increase in the intercept. Thus, the larger effect on the intercept (encoding), in combination with an observed effect on the slope (comparison), argues against the Class C theory which predicts only an effect on the intercept. In other words, the major effect of test-stimulus degradation is on encoding, but

degradation was shown to influence the comparison operation as well. In accordance with the Class B theory, Sternberg concluded that the representation of the stimulus in memory takes the form of physical properties rather than the name of the character as would be the case under the Class C theory. A further analysis of the data reaffirmed the exhaustive scanning theory in that the reaction times were linear, suggesting a serial process; the slopes of the latency functions for positive and negative responses were nearly identical, suggesting exhaustive scanning rather than self-terminating scanning.

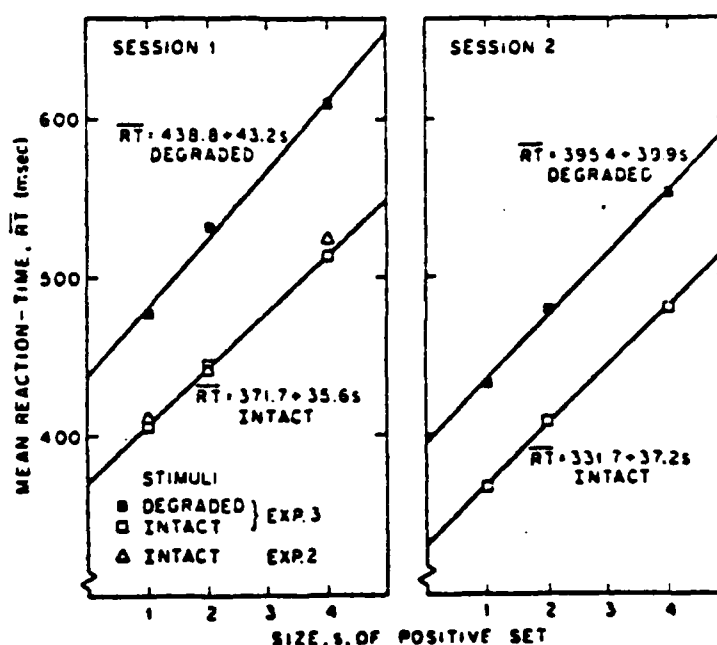


Figure 7. Memory search times as a function of memory set size and clarity of test digits (Sternberg, 1967).

Sternberg's work up to this point was grounded in Donders' Stage Theory. He was more than aware of the classical criticism that surrounded Donders' Subtraction Method and attempted to allay similar criticism of his own work. He investigated (1969a) various assumptions about stage

durations that had been recently reported. The three assumptions, shown in Figure 8, were: (1) there are successive functional stages between stimulus and response, whose durations are additive components of reaction time (Donders' idea); (2) reaction time components are stochastically independent; and (3) the forms of components can be specified as exponentially-distributed stage durations. Almost always, a 'strong' model had been tested in which the proposition of main interest was combined with both of the supplementary ones. Sternberg viewed assumption one as the main assumption to be tested. However, he believed that rather than testing assumptions two and three as supplementary to assumption one, each assumption should be tested separately. In defense of this position, he argued that if a test of the main proposition, together with supplementary ones, failed, it would be difficult to decide which of its several assumptions was at fault; also, the strong model approach allowed for the possibility of different sets of components giving rise to reaction time distributions that had approximately the same form.

These thoughts on testing assumptions of stage durations and the results of his prior experiments, led to the publication of his seminal paper, "The discovery of processing stages: extension of Donders' method" (1969). In this paper, Sternberg presented a more complete description of the information processing stages underlying memory scanning and a methodology for studying mental processes. Sternberg described the memory scanning process as involving four additive stages: stimulus encoding, serial comparison, binary decision, and response organization. Additivity means that: (1) the times for each stage contribute separately to the total processing time. Therefore, total reaction time is the sum of the times for each separate stage,

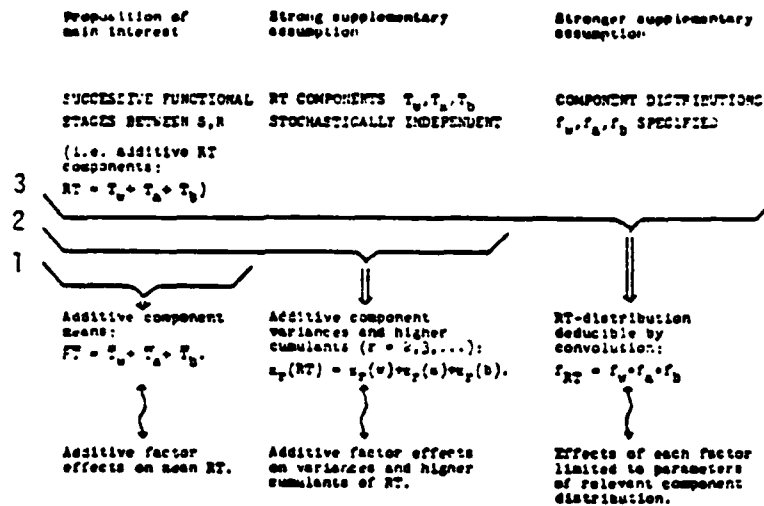


Figure 8. Three types of assumption in the decomposition of RT, and their implications. Wavy arrows show loose implications; statements in bottom row apply only to experimental factors that influence no stages in common. Here  $T_a$  and  $T_b$  are random variables representing the durations of two different stages, and  $T_w$  is a wastebasket category representing the total duration of all other events between stimulus and response. Line 1 represents a test of the main assumption and the implication that the mean RT is the sum of the means of the components. Line 2 represents the main assumption taken together with the first supplementary assumption. This test has strong implications for independence since not only are the component variances additive but all the higher cumulants are additive as well. Line 3 represents an even stronger supplementary assumption taken together with the other two assumptions because it specifies the forms of the component's distributions. Given the distributions and the other assumptions, one can deduce the RT distribution itself (Sternberg, 1969a).

and, (2) if one stage is slowed or speeded in some manner the times for the other stages are not affected.

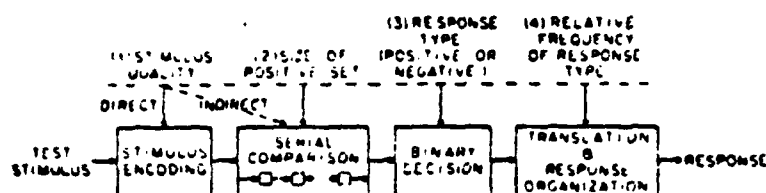


Figure 9. Processing stages in binary classification. Above the broken lines are shown the four factors examined. Below the line is shown the analysis of RT inferred from additive relations between factor pairs 1 & 2, 1 & 3, 2 & 3, 2 & 4, and 3 & 4, the linear effect of factor 2. The quality of the test stimulus influences the duration of an encoding stage in which a stimulus representation is formed. This representation is then used in a serial-comparison stage, whose duration depends linearly on size of positive set; in each of its sub-stages the representation is compared to a memory representation of one member of the set. In the third stage a binary decision is made that depends on whether a match has occurred during the serial-comparison stage that precedes it; its mean duration is greater for negative than positive decisions. The selection of a response based on the decision, is accomplished in the final stage whose duration depends on the relative frequency with which a response of that type is required (Sternberg, 1969a).

Taking these properties of additivity into consideration, Sternberg re-analyzed his earlier experiments and studied the effects on reaction time of those factors he had manipulated. The factors under study are shown in Figure 9 above the dotted line: stimulus quality, size of positive set, response type, and relative frequency of response type. To illustrate, the comparison stage as measured by the reaction time slope is unaffected by the variables that influence the encoding stage (e.g., stimulus degradation, based on 1967 results), the response stage, and the response organization stage. These variables are additive and do not interact. To take another example, See Figure 10.

Suppose there are three stages a, b, and c that occur between stimulus and response. Then suppose that there are three factors F, G, and H, such that factor F influences only the duration of a, factor G influences only the duration of b, and factor H influences b and c, but not a. The likely relations of the three factors on mean reaction time are that when factors influence no stages in common, their effects on mean reaction time will be independent and additive. Thus, factors F and G should have additive effects on mean reaction time. On the other hand, when two factors G and H, influence at least one stage in common (stage b) there is no reason to expect their effects on reaction time to add; the most likely relation is some sort of interaction.

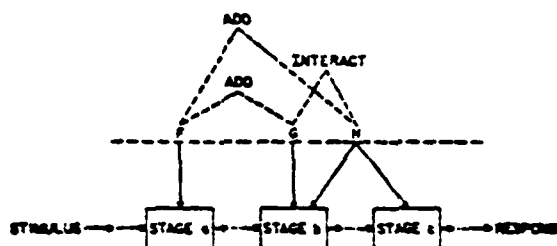


Figure 10. Example of an arrangement of stages (a, b, and c) and factors (F, G, and H). Below the horizontal line are shown three hypothetical stages between stimulus and response. Horizontal arrows represent inputs and outputs of stages; time proceeds from left to right. Dots indicate the possibility of other stages in a string in which the hypothetical stages are embedded. Arrows are drawn from factors to the stages assumed to be influenced by those factors. Above the line are indicated the relations among effects of the factors on mean reaction time that are expected from the arrangement (Sternberg, 1969a).

In his work, Sternberg makes an important revision of Donders' first assumption based on "pure insertion" tasks by replacing it with a weaker assumption of "selective influence." That is, instead of requiring that a change in the task would insert or delete an entire processing



stage without altering others, the weaker assumption demands only that the amount of processing required by an experimental manipulation influence the duration of a stage without altering others. Figure 11 illustrates the weaker assumption. To estimate the comparison time by Donders' Subtraction Method, one would have to study Task 2 in which the positive set size is one, then compare it to Task 1. Task 1 would have had to have been constructed to measure the zero-intercept directly (simple reaction time) by deleting the comparison stage entirely. However, Sternberg seriously doubted whether an appropriate Task 1 could be devised whereby deletion of the comparisons would leave the other stages of processing invariant, thereby acknowledging the flaw in the pure insertion assumption.

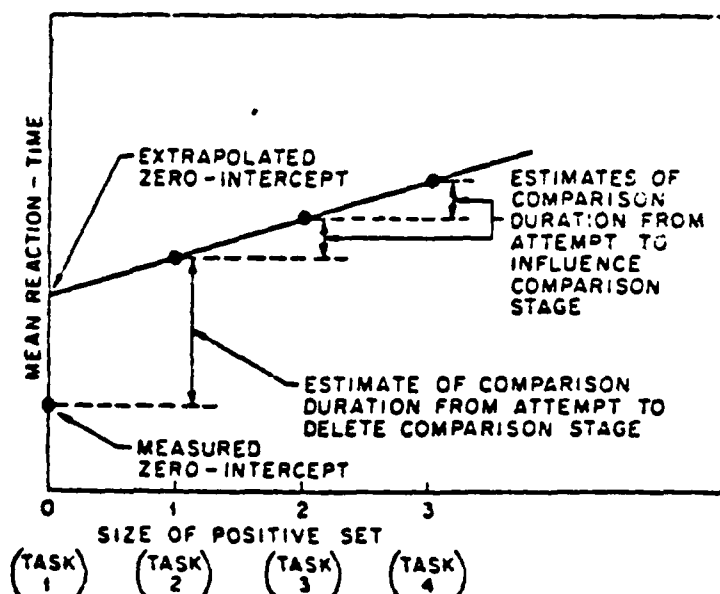


Figure 11. Example of error from hypothetical attempt to estimate comparison time by deleting the comparison stage altogether, as in the subtraction method, and to use a measured zero intercept. Attempt fails because deletion of comparison stage changes the demands placed on other stages, whereas variation of the number of comparisons,  $s$ , ( $s \geq 1$ ) does not (Sternberg, 1969b).

Consequently, Sternberg suggested that the important comparisons were between Tasks 2 and 3, 3 and 4, and so on. Then the interpretation requires only that the comparison stage be selectively influenced by set size. Moreover, rather than eliminating a stage, for example, encoding, Sternberg was able to examine the effects of making the encoding process of discrimination more or less difficult, thereby varying the amount of work the stage had to accomplish. The result is that one does not have an estimate of the total duration of the stage. But, what is important is the validation of the existence of a stage, what influences it, and its relation to other stages.

The logic of Sternberg's methodology can be seen in his analysis of the memory-scanning experiment which is based on two techniques: the subtractive method and the additive-factors method. Recall that the subtractive technique rests on the assumption that if the time to search  $n$  items is subtracted from the time to search  $n + 1$  items, the difference is an estimate of the time for a single memory comparison. Thus the slope of the time relating reaction to the number of items to be searched is an estimate of the memory-search rate.

Sternberg's analysis of Donders' subtractive method is important because it avoids the problems associated with the fallacy of pure insertion. In Sternberg's revision, no stages are deleted or inserted. Instead, in order to measure the duration of a stage, the experimental manipulation is to vary  $n$ , the number of times the stage operates. Actually, the method never requires constructing an experimental task where the stage of interest is missing; the time for this hypothetical task is "extrapolated mathematically by computing the intercept, presumably the time for all other components except the one of interest, since  $n = 0$  at that point" (Chase, 1978).

The additive-factors method rests on the assumption that mental processes are organized into a series of stages such that each stage operates on its input independently by the next stage, and so on. The amount or complexity of processing at any stage depends then on its input (or the factor that influences it) and not directly on the amount of complexity of processing at other stages. One stage influences another only indirectly and this is by the information that is passed between them.

A further contribution to the additive-factors method was a test of the idea that reaction time components are stochastically independent, that is, there is no correlation between durations of various stages. The assumption that stage durations are additive has often been incorporated with the idea that they are independent. Such an assumption has powerful consequences. Only if stage durations are independent can one have some belief in his hypothesis being tested. A persistent failure to find independence might cast suspicion on either the existence of stages, or the appropriateness of the experimental method to study them (Sternberg, 1969, p. 304). Alternatively, it is possible to have processing independence without stochastic independence. As an example, Sternberg considered what would happen if a subject were 'prepared' on particular trials for a stimulus-response pair. If the stimulus was one the subject was prepared for, both the encoding and comparison stages would be shorter than they otherwise would be. Preparation can be viewed as a factor that influences both stages; however it is under the subject's control rather than the experimenter's and can vary in level from trial to trial. The net result would show that the component times for the various stages to be correlated. Under these circumstances, the average

component times would still be additive, but the variances would not be.

Sternberg argued that as long as the variation of the subject-controlled factor was not influenced by levels of the experimenter-controlled factors, its variation would not disrupt the independence of stage-duration means or the additivity of factors that influenced the two stages separately. In determining whether the definition of stage should include a requirement of stochastic independence, he, in fact, suggested that assumptions of additivity and independence always be examined separately. He further suggested that stochastic independence be retained, but that this property be conceived of as "easily camouflaged, revealing itself only in highly refined experiments" (Sternberg, 1969a, p. 303).

This method, then, has two important consequences for the analysis of latencies. First, the mean duration of a stage depends only on its inputs and the operations it performs, and thus each stage contributes an additive component to the total reaction time. Second, variables that influence separate stages should have additive effects on the total duration time; hence, they should not interact. According to Sternberg (1969a) the existence of additive stages is established empirically by the discovery of subsets of experimental variables that interact within each subset but are additive across subsets. Thus, as in memory scanning experiments, one can test this hypothesis about stages with specified functions if two factors can be found that influence the intercept of the reaction time function and not the slope, that is, that neither variable interacts with memory load. Thus, the implication is strengthened that encoding and comparison exist as two additive stages.

The additive-factor method cannot distinguish processes, but only

processing stages. If an interaction is uncovered, one can reject the idea of separate stages (i.e., no stage influenced by both factors). But it does not allow one to reject the more general proposition of separate processes. The subtractive technique, on the other hand, is useful in actually measuring these mental processes. In the case of memory scanning, for example, Sternberg was presumably able to measure the duration of the memory-comparison process as well as to infer some of its properties (serial, exhaustive).

The power of the additive-factors method arises in conjunction with the subtractive technique (Chase, 1978). Once a method is established for measuring the duration of a mental operation (the subtractive method), then one can establish its invariance. That is, if a parameter purports to measure a mental process, then it should remain invariant across variables that theoretically have no influence on that mental process, hence the additive-factors method.

Although Sternberg is generally credited with providing the impetus for renewed interest in using reaction time measures, he also set the tone for the work in the mid-1960's of Posner and his colleagues. First, this work complemented Sternberg's by its reintroduction of Donders' subtractive technique to investigate levels of processing in simple classification tasks. Second, because of a sound information processing theory, the work of Posner and his colleagues is important because much of our immediate processing is based on the different types of representations they discovered. Posner and his colleagues were the first to investigate experimentally these representations while laying the theoretical foundations for later work in the area.

Posner and Mitchell (1967) performed a series of studies using

classification tasks. The goal of this research was to find levels of processing which depended on physical attributes of the stimuli and those which relied on more detailed analysis such as naming attributes or relation to a superordinate. The devised task required that subjects process information at different levels within the same experiment.

The chosen stimuli were pairs of letters, digits, or nonsense forms. What was varied was the level of instructions that the subjects used to base their classifications. Level 1 instruction involved classifying each pair as 'same' if a physical match (e.g., AA) could be made, and 'different' if there was no physical match. Similarly, Level 2 instructions involved the subject classifying a pair as 'same' if a name match (e.g., Aa) could be made, and 'different' if not; in Level 3 instructions, a 'same' response was required if a rule match (e.g., both vowels or consonants) could be made, and 'different' if not.

By use of the subtractive method, times for matches at each level were analyzed. A comparison of Level 1 with Level 2 instructions showed a clear difference in reaction time at a rate of 71 msec. Physical matches were faster than name matches. Based on these results, Posner and Mitchell identified two levels of processing or types of codes. The first is based on physical identity and includes letter pairs which are identical in form. The second code is based on name identity and involves matching letters which have no obvious physical similarity. One significance of this finding lies in the fact that physical identity is free of prior learning effects since both letters are presented together in the perceptual field. It is logically possible for the match to be made even if the stimuli had never been seen before. On the other hand, for a name match, the subject must derive something like the name

in order to make the match.

To assess the processing involved in a higher order classification, times to process Level 2 instructions were compared with reaction times for Level 3 instructions. The difference between the two showed a faster reaction time for name identity than for rules identity. On this basis, rule identity was considered as a third mode of processing. (Figure 12 shows the times for different processing of all three processing levels.)

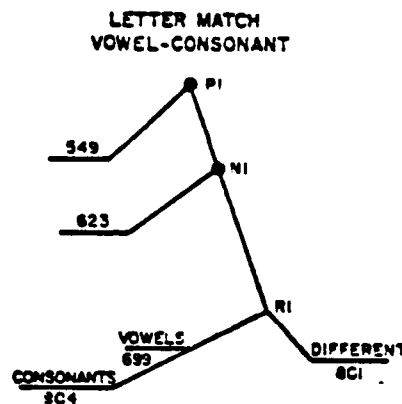


Figure 12. Reaction times for physical (PI), name (NI) and rule (RI) level matches for letter pairs (Posner, 1972).

An interesting anomaly of the above experiment was that it was possible to obtain reaction times which lay between the physical and name code. This occurred for a stimulus pair that was not physically identical but possessed considerable similarity (e.g., Cc). Posner and Mitchell explained this phenomenon as representing not an average of the reaction times for physical and name responses, but as representing the amount of time necessary for processing of the nonidentical pairs. They suggested that at least two fundamental mechanisms might

account for reaction times intermediate between physical and name codes. The first was a serial process with physical identity and name identity at the ends of a continuum involving the degree of similarity between the pair. The second view was parallel processing whereby the naming process went on independently of any matching on the basis of similarity.

Posner and Mitchell argued that the consistency of the calculated times between the different processing levels and the relative stability of the code differences with practice and level of instruction reaffirmed the use of the subtractive method. However, they were very cautious not to interpret their results as confirmation of either serial or parallel processing. Their experiment was not designed to answer that question. But, they suggested that it appeared possible that increasing times for the different codes might be a result of either serial or parallel processing. In addition, some aspects of the processing may be parallel and others serial. Retrospective accounts from their subjects made it reasonable to assume that all subjects derived the name of letters before proceeding to analyze whether they were both vowels or both consonants. This suggested serial processing. On the other hand, the fast times for matching letters which were similar but not identical seemed to argue that the process went on in parallel with the task of deriving the letter names. Further tests of these notions were required.

Posner and Keele (1967) were able to use the subtractive technique to discover a previously unsuspected level of visual presentation. They presented subjects with two letters of the alphabet, sequentially, and subjects then made a rapid "same" - "different" judgment. Posner and Keele found that "same" reaction times were almost 100 msec faster if the letters were physically identical than if the letters had the same name,



but the difference disappeared if the second letter was delayed a second or two. This seemed to suggest that the loss of visual information forced people to make their same-different judgment on the basis of the more easily retained name of the letter. In a further study, Posner and his colleagues (Posner, Boies, Eichelman and Taylor, 1969) showed that physical match advantage was not peculiar to matching upper-case letters, since lower-case physical matches facilitated reaction times in the same way. These three studies all suggested different codes; however Posner (1969) confirmed their isolability when he showed how visual and name codes could be independently manipulated.

Figure 13 illustrates some of the means of manipulating the times for matches based upon visual and name codes. As an example, Posner (1969) showed that if a visual letter were presented for .5 seconds and then removed, increasing the delay before presenting a second letter to be matched increased the time to make a physical match but not the time to make a phonetic match. Under these conditions, the selective effect of delay on the physical code eliminated the reaction time difference between

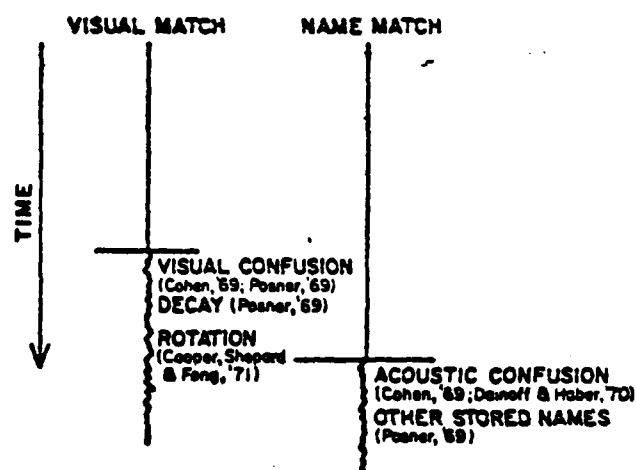


Figure 13. Some of the factors that have been shown by various investigators to affect physical and name matches. The two lines represent assumed parallel processes. The times for each kind of match can be manipulated by the factors listed (Posner, 1972).

name and physical matches after a 2 sec interval. This task was only one instance of the use of the confusability technique to prove isolability of the visual and phonetic code.

An important consequence of Posner's work revolves around the issue of serial versus parallel processing. It raised the question of whether the complexity or nature of the task would determine which processing mode was activated. The results of further studies (e.g., Egeth, 1966; Egeth, Jonides, Wall, 1972) on the issue provided information for a new way of thinking about serial and parallel processing. Today, an analysis of the issue would be made in terms of the amount of automaticity and directed attention that various components of a task required.

Posner's efforts to establish levels of processing have had significant consequences, also. His work proved the power of reaction time through its use in isolating independent subsystems (memory codes). This finding has important implications for reading. Posner suggested that if words or letter strings conformed to the analysis of codes that he presented, then further studies would indicate evidence for separate visual, phonetic, and semantic codes. Further, subjects would show an ability to select among the codes depending on which level of reading was required of them.

### CHAPTER THREE

Reading, a rich multi-stage, complex mental process is the vehicle through which insights into cognitive processing have been made. Moreover, the questions explored by Sternberg and Posner, and the findings that resulted from their work have had a profound effect on the ways in which reading theorists have conceptualized the reading process itself. The work by Sternberg generated information regarding the mental processes that underlie the management of active memory. It influenced the development of a sound information processing theory enriched by knowledge of the stages involved in memory scanning, the revision of the subtractive method, and the additive-factors method. Posner defined levels of processing in memory by proving experimentally that there were three memory code systems (visual, phonological, semantic). This research has laid the groundwork for a rigorous theoretical treatment of the reading process.

For example, in reading, visual processing of text activates representations of stimulus patterns. These patterns are compared with representations in memory of patterns previously encountered. Familiar patterns such as syllables, words, or larger language units are recognized and by way of associative processes activate components of the semantic memory system that constitute or generate the meaning of the material perceived. A problem that has occupied reading theorists is to explain with greater precision how these processes of comparison between sensory input and memory are accomplished.

The LaBerge and Samuels (1974) model of the reading process represents the manner in which reading theorists use mental findings to address the above problem. Its value has been in its incorporation of

stage theory, memory coding processes, and the role of attention to analyze various subprocesses of one component of reading: word analysis.

LaBerge and Samuels began with the premise that "the journey taken by words from their written form on the page to the eventual activation of their meaning" (1974, p. 548) involved several stages of information processing. They assumed that a person could attend to only one thing at a time but could do many other things simultaneously if none of them required attention. Since reading involves doing many things simultaneously, the reader must learn to perform low level skills automatically, that is, without attention. The reader would then be able to attend to the implications of what was being read rather than to decoding the printed word.

The basic model consists of three memory code systems: visual memory, phonological memory, and semantic memory. Each system holds different representations of the input and is associated with the other through the proposed hierarchical stages of visual input—→ feature detector—→ letter coding—→ spelling pattern coding—→ memory coding—→ response.

Figure 14 represents a model of the coding of visual patterns according to LaBerge and Samuels. Visual stimuli are transformed by the visual system and excite certain feature detectors in memory. Because of previous learning, certain combinations of features map onto letter codes. Accordingly, if these features are simultaneously present, they automatically give rise to the appropriate letter. Letter codes can then be mapped onto spelling pattern codes which can be mapped onto word codes. LaBerge and Samuels relied heavily on the hierarchical schemes of Estes (1972).

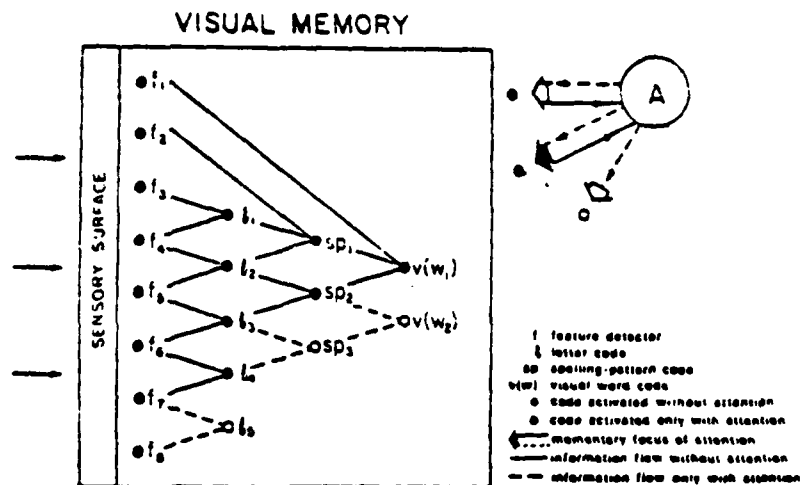


Figure 14. Model of visual memory showing two states of perceptual coding of visual patterns. Arrows from the attention center (A) to solid-dot codes denote a two-way flow of excitation: attention can activate these codes and be activated (attracted) by them. Attention can activate open-dot codes but cannot be activated (attracted) by them (LaBerge & Samuels, 1974).

To the extent that these mappings are stored in long-term memory because of previous learning, the recognition of the various units can occur automatically. If they are not in long-term memory (and not automatic), the attention mechanism is necessary to establish new codes in long-term memory. For example, if the reader is presented with an unfamiliar letter, the feature detectors can activate the attention mechanism which allows the reader to process and organize the features into a new letter code.

The role of the attention mechanism is considered to be critical in early learning of the graphemic code, but expendable in later stages of reading. The limited capacity property of attention is characterized by the fact that the attention center can activate only one code. The attentional activity as conceptualized may then have three effects on

information processing. First, it can assist in the construction of a new code by activating subordinate input codes. For example, in Figure 14, successive activation of  $f_7$  and  $f_8$  is necessary to synthesize  $l_5$ . Second, activation of a code prior to the presentation of its corresponding stimulus is assumed to increase the rate of processing when that stimulus is presented (LaBerge, Van Gelder, and Yellott, 1970). Finally, activation of a code can arouse other codes with which it is associated.

The role of perceptual learning in reading was a major consideration of LaBerge and Samuels. LaBerge (1973a) showed that familiar stimuli such as tones and color patches might be perceptually analyzed while attention was directed elsewhere. These findings suggested that perception of unfamiliar patterns might require the assistance of attention. Using these results and a combinatorial procedure of Donders' (1868/1969) 'c' method and a cueing technique (LaBerge, et al., 1970), LaBerge (1973b) provided an experimental demonstration of the perceptual learning of letter codes.

He used the familiar letters b, d, p, q and the unfamiliar letters f, l, 1. Other groups of letters, for example, a, g, n, s, were used as cues in order to focus the subject's attention at the moment a pair of test letters were given. The subject was instructed to press a button as rapidly as possible if the second letter was the same as the first cue letter. LaBerge assumed that this task focused the subject's attention on the letter code of the first letter. On roughly one out of five trials, however, the cue letter was followed by a pair of letters rather than a single letter. If these letters were the same, the subject was also to press the button, regardless of the name of the cue letter. Some of the trials were the familiar letters, while others were the unfamiliar

letters. Thus, the subject pressed the button on two types of trials: one on which he was expecting that particular letter, called a primary trial; and one on which he was not expecting a particular pair of matching letters, called a secondary trial. The important comparisons would then be between latencies of new and old letters under primary (nonswitch) and secondary (switch) conditions.

LaBerge and Samuels hypothesized that, initially, latencies of unfamiliar test letter matches would be longer than the familiar letter matches, but that the amount of difference would decrease with practice if perceptual learning were taking place. The results from sixteen subjects are shown in Figure 15.

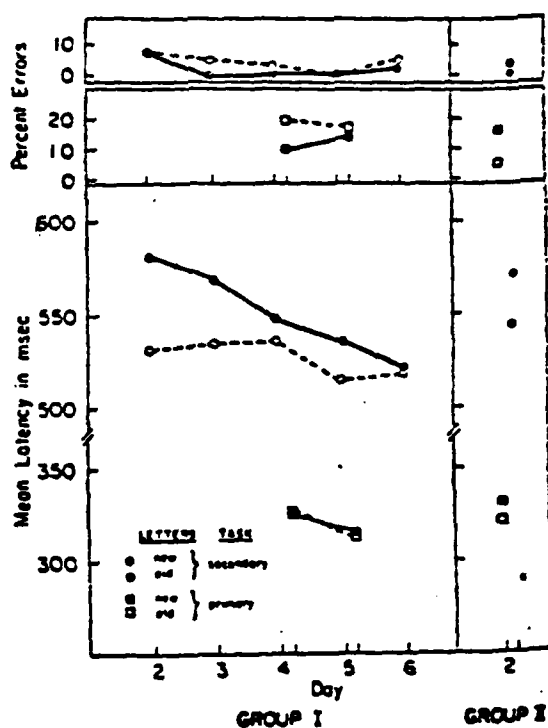


Figure 15. Mean latencies and percent errors to new and old letters under primary and secondary test conditions. Each group contained 16 Ss (LaBerge, 1973b).

The initial difference in latency between unfamiliar and familiar letters was 48 msec. This difference was interpreted as a measure of the time it took the subjects to switch attention. The extra processing time for a letter which involved a switch in attention, for example, served as an indicator of automaticity. With continued practice the reaction times decreased, until there was no difference on the fifth day of the experiment. Referring to the model in Figure 14, LaBerge and Samuels (1974) suggested that the dashed lines between  $f_7$  and  $f_8$  and  $l_5$  were strengthened over time and approached the automatic level of learning represented by the lines connecting  $f_6$  and  $f_7$  and  $l_4$ . Taken together, the data strongly suggested that over a period of five days, what was learned was a perceptual process that operated without attention, namely an automatic perceptual process, although the nature of the process was not decided by the data (LaBerge and Samuels, 1974, p. 559).

After visual recognition, the input can make its way to meaning by a number of different routes in the model. In Figure 16, all the memory systems relevant to LaBerge and Samuels' (1974) theory of reading are shown together. Visual codes can be mapped onto phonological codes which are then mapped onto higher-order phonological codes or onto meaning codes. LaBerge and Samuels (1974) also allow the possibility of a direct mapping of a visual code onto a meaning code. They do not state which is more common for the fluent, skilled reader. However, the direct visual-to-meaning mapping seems to be required to handle the exception, such as homophones (e.g., bear, bare), rather than the rule. Finally, with the help of attention, a visual code may be mapped onto an episodic code. A reader may not be able to pronounce a word, but by some mnemonic strategy, rule, or image, a recognition may occur. This association could allow a connection with the phonological code, which could then be mapped



onto meaning.

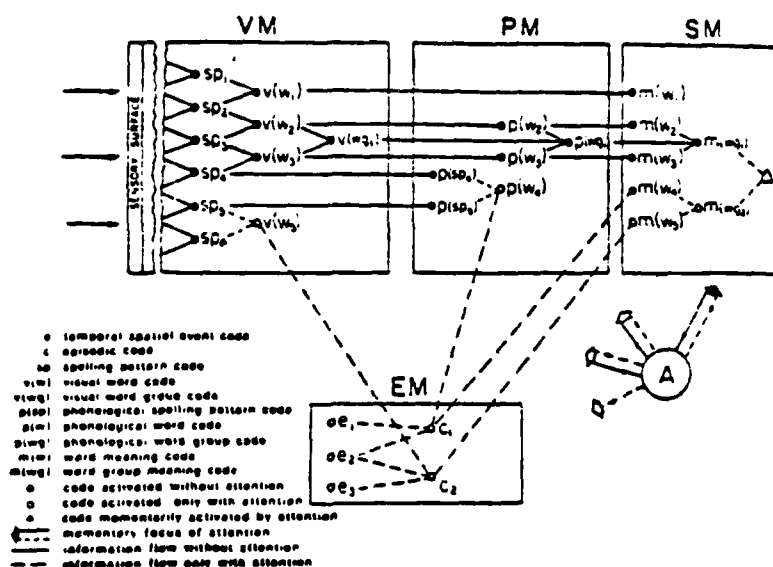


Figure 16. Representation of some of the many possible ways a visually presented word may be processed into meaning. The four major stages of processing shown here are visual memory (VM), phonological memory (PM), episodic memory (EM), and semantic memory (SM). Attention is momentarily focused on comprehension in SM, involving organization of meaning codes of two word-groups (LaBerge & Samuels, 1974).

LaBerge and Samuels acknowledged that their model of the reading process was not complete. Their principal aim, however, was to help clarify some locations "of ignorance and point the way to the kinds of experiments and theoretical operations most likely to remove that ignorance" (1974, p. 560). In this respect the model was successful. First, the model contributed significantly to the definition of the stages of information processing involved in reading, drawing upon the available experimental literature in memory processing. Second, it bridged the gap between those models of reading which viewed the reading process as strictly serial in nature (e.g., Gough, 1972) and those findings (Posner, 1969; Egeth, 1966, 1972) which implied parallel processing. This set the

stage for information processing models which would view the reading act as an interactive process (Rumelhart, 1977).

Just as the usefulness of the LaBerge and Samuels model of reading cannot be overlooked, neither can its limitations. As a model of reading, it is fairly representative of most of our models in that it tends to illuminate one component of the reading process while neglecting others. For example, LaBerge and Samuels (1974) and Gough (1972) focus on the word analysis component including graphemic encoding, translating orthographic patterns into sound patterns and so on while the model of Kintsch (1974) and Kintsch and van Dijk (1978) focus on comprehension, specifically the process of integration. This is not to say that these models do not acknowledge other aspects of processing, but simply that they describe detailed mechanisms for one aspect of reading and no comparable mechanisms for other stages.

To address the need for a truly interactive model that describes mechanisms for both the word analysis and discourse analysis components, theorists must focus on: (1) building models that identify the component skills involved in reading from decoding the printed word, to analyzing and comprehending text, and to integrating contextual and perceptual information in encoding words and phrases; and, (2) building models that enable diagnosis of the sources and nature of reading difficulties. It follows from this that acquiring data on individual differences is crucial. The ongoing efforts of reading theorists to meet these challenges are represented in the research of Weaver and Frederiksen (1980) and Just and Carpenter (1980). That these researchers are attempting to build models which are broad enough to encompass the multidimensions of reading, while at the same time are precise enough to allow for the discovery of

individual differences in separate aspects of each dimension is nontrivial. Nor are the theoretical issues that they are investigating. Moreover, the theoretical views guiding their study of reading have implications for the way in which component processes are measured. Measurement of skills and processes is not an incidental aspect of a theory, but instead both reflects the theory and influences interpretations of experimental data.

Just and Carpenter (1980) use eye fixations and reading times to reveal real-time characteristics of reading. The useful property of these methodologies is that they can measure reading time on successive units of text, thereby enabling precise charting of reader-text interactions. Like reaction time measures, eye movement data permit inferences to be made about reading performance "on-line." This is perhaps the best window we have on cognitive processing.

Weaver and Frederiksen (1980) use reaction time to measure interactions between reader skill and text structure variations. They measure changes in the processing efficiency of readers of differing skill levels as text-structure variables are manipulated to increase in their complexity. Preliminary work indicates that good and poor older readers do not differ so much in accuracy. But differences are reflected strongly in the speed of processing information. For example, it is not that poor readers are unable to comprehend texts, but they pay a higher price than good readers as text structure becomes more complex and textual cues to meaning become more subtle. This is because their lower level skills are not fully automated and therefore, decrements in speed on separate component processes accumulate

Theirs is a model of individual differences, each feature of it

designed to distinguish good readers from poor readers, and instructional experiments are built into the validation of their theoretical model. Such efforts--those which are both broad and precise and combine theoretical and instruction validation of reading processes and skills--are promising for advances in both theory and practice of reading.

The use of reaction times has already shown its value in informing reading researchers in their efforts to build models of reading. In particular, the subtractive method for analyzing reaction times has proven its value as a technique for deriving measurements that reflect a single locus of information processing. Hopefully, its present use by reading theorists will continue to guide the development of ever more precise models of the reading process.

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## FOOTNOTE

<sup>1</sup>The "eye and ear" method consisted of making an observation by noting, to one-tenth of a second, the time at which a given star crossed a given wire. (The field of the telescope was divided by parallel cross-wires in the reticle.) The observer looked at a clock, noted the time to a second, began counting seconds with the ticking (beats) of the clock, watched the star cross the field of the telescope, noted and "fixed in mind" its position at the beat of the clock just before it came to the critical wire, estimated the place of the wire between positions in tenths of the total distance between positions, and added these tenths of a second to the time in seconds that he had counted for the beat before the wire was reached (Boring, 1929, p. 134).

## APPENDIX I

Stages Involved Between Stimulus and Response  
in Assessing Physiological Time

- (1) the action on the sensory elements in the sense-organs;
- (2) the communication with the peripheral ganglion cells and the increase required for a discharge ('Schwelle' of Fechner);
- (3) the conduction in the sensory nerves up to the ganglion cells of the medulla;
- (4) the increase in activity in these ganglion cells;
- (5) the conduction to the nerve cells of the organ of conception;
- (6) the increase in activity of these nerve cells;
- (7) the increase in activity of the nerve cells of the organ of will;
- (8) the conduction to the nerve cells governing movement;
- (9) the increase in activity in these cells;
- (10) the conduction in the motor-nerves to the muscle;
- (11) the latency in the action of the muscle;
- (12) the increase in activity up to the moment of overcoming the resistance of the response;

## APPENDIX II

Results Obtained in Experiments with Five Vowel-Symbols,  
Carried Out with Three Subjects of Different,  
and Generally Young Ages

	second
(1) stimulation of the <u>skin</u> ; choice, calculated from the averages	0.666
(2) stimulation of the <u>eye</u> ;	
(a) two colours, choice, five subjects, calculated from the averages, 0.184, 0.122, 0.159, 0.134	0.172
(b) two vowel-symbols, choice, calculated from the averages	0.166
calculated from the minima	0.124
(c) five vowel-symbols, calculated from the averages	0.170
calculated from the minima	0.163
(3) stimulation of the <u>ear</u> ;	
(a) two vowel-sounds, calculated from the averages	0.056
calculated from the minima	0.0615
(b) five vowel-sounds, with myself, initially, calculated from the averages	0.088
later, calculated from the averages	0.083
calculated from the minima	0.067
The same with four other subjects	
calculated from the averages	0.088
calculated from the averages	0.069
calculated from the averages	0.087
calculated from the averages	0.088

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